Lightweight Innovations for Tomorrow (LIFT): Fuel saving potentials for heavy-duty vehicles, trains, ships, and aircraft

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LIGHTWEIGHT INNOVATIONS FOR TOMORROW

CENTER FOR SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

LIFT Mission

- Accelerate the development and application of innovative lightweight metal production and component manufacturing technologies to benefit the US transportation, aerospace and defense market sectors.

One of the Manufacturing Innovation Institutes: Putting America at the Forefront of 21st Century Manufacturing

- **LIFT brings together > 100-member organizations that pair the world's leading _aluminum, titanium, magnesium and high strength steel_ manufacturers** with universities and labs pioneering new applied technology development and research to deliver high value advanced alloy processing technologies that reduce the weight of machines that move people and goods on land, sea and air.

https://lift.technology/

Public-Private Partnership Ecosystem

Industries & Professional Societies

- ASM International
- Alcoa
- Boeing
- DNV·GL
- Comau
- Eaton – Powering Business Worldwide
- AAM
- GE
- Huntington Ingalls Industries – Hard Stuff Done Right
- Nemak
- AFS
- United Technologies Research Center
- GKN Aerospace
- AWS
- Metalsa – Quality as a way of life
- Lockheed Martin
- Grede – Casting Integrity
- Tenneco
- Materion
- esi – get it right®
- Thermo-Calc Software
- Metal Powder Industries Federation – MPIF
- NADCA – North American Die Casting Association
- MAMA – Michigan Aerospace Manufacturers Association
- ABS

Academic & Research Partners

- Northwestern University
- EWI
- The Ohio State University
- Michigan
- UK University of Kentucky
- Penn State
- Battelle – The Business of Innovation
- Michigan Tech – Michigan Technological University
- Case Western Reserve University – Est. 1826
- Colorado School of Mines – Earth • Energy • Environment
- Johns Hopkins University
- MIT – Massachusetts Institute of Technology
- Michigan State University
- Purdue
- University of Notre Dame
- The University of Tennessee Knoxville
- WPI
- Wayne State
- SwRI
- UNT

Small/Medium Manufacturers

- Product Development Analysis
- Xtalic
- New Star Metals
- AEM
- Böllhoff
- Easom Automation – A Lincoln Electric Company
- SCM Metal Products
- Laser Mech
- Flash Bainite – Maximum Strength Steel
- Quality Metalcraft
- Gehring
- Ricardo
- Manufacturing Technology, Inc.
- Optimal Process Technologies, LLC
- Optomec
- Terves – Engineered Response
- The NanoSteel Company, Inc.
- MesoCoat
- DEFORM
- FRA Composites®
- Luvata
- Coldwater Machine Company

Start-ups

- cie-metalworks
- JoyWorks
- Scimplicity
- Airflow Sciences Corporation
- Huys
- Thixomat
- Engineered Performance Materials
- QuesTek Innovations LLC
- Fabrisonic
- Commander Innovations
- Aristo Cast Investment Casting
- Phinix
- Detroit Materials

Workforce/Education

- Macomb Community College – Education • Enrichment • Economic Development
- Ivy Tech Community College
- Magnet
- CAR – Center for Automotive Research
- Focus: HOPE – Celebrating Diversity Since 1968
- WIN – Workforce Intelligence Network
- Columbus State Community College
- Conexus Indiana
- Pellissippi State Community College

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LIFT LCA Crosscut

Organization

Pillars

- **Melt processing**
- Powder processing
- Thermo-mechanical processing
- Agile processing
- Coatings
- Joining and Assembly

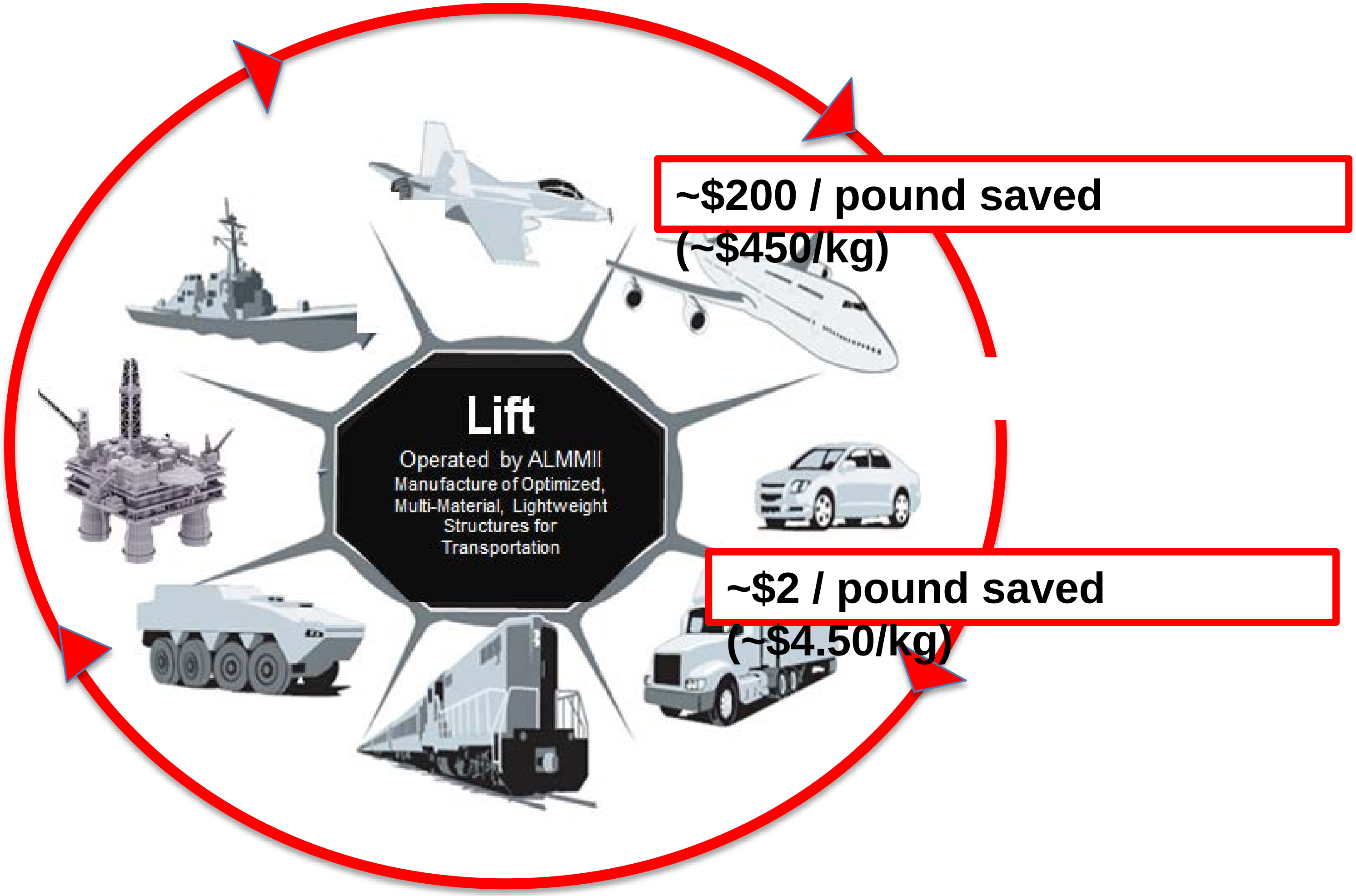
Projects (e.g.)

- Thin-wall ductile cast iron
- Thin-wall aluminum die castings (upcoming)

Crosscut

- ICME
- Design
- **LCA**
- Validation/Certification
- Cost modeling
- Supply chain
- Corrosion
- Ballistic/Blast

LIFT technology portfolio



INCREASING VALUE OF WEIGHT REDUCTION & DECREASING UNITS/YEAR

Fuel Saving Potentials

- OEM pathways to reduce use phase fuel consumption (FC) across modes in the US
  - Advanced and more efficient powertrains
  - Vehicle mass (M_{vh}) reduction – our focus here
- Key fuel use metrics across transportation modes:
  - FC and Fuel Intensity ($FI = FC/M_{cargo}$)
  - Both are dependent on Fuel Reduction Value ($FRV = \Delta FC/\Delta M$)
- LW Manufacturing Technologies enable a ΔM_{vh}
  - Part and component LW
  - Shipping container LW across modes
- ΔM_{vh} also impacts other phases of vehicle life cycles

Fuel Consumption by Mode in US

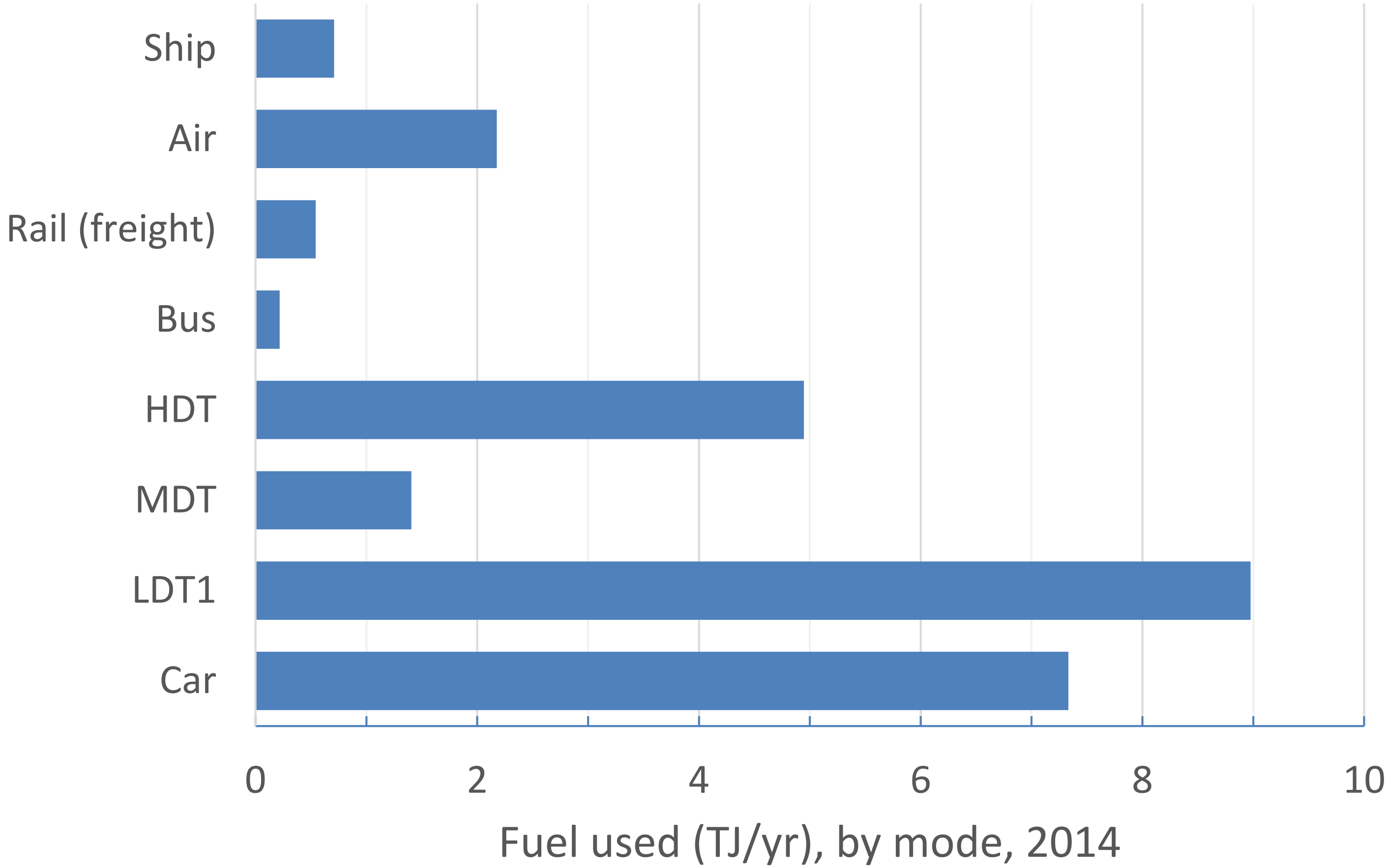
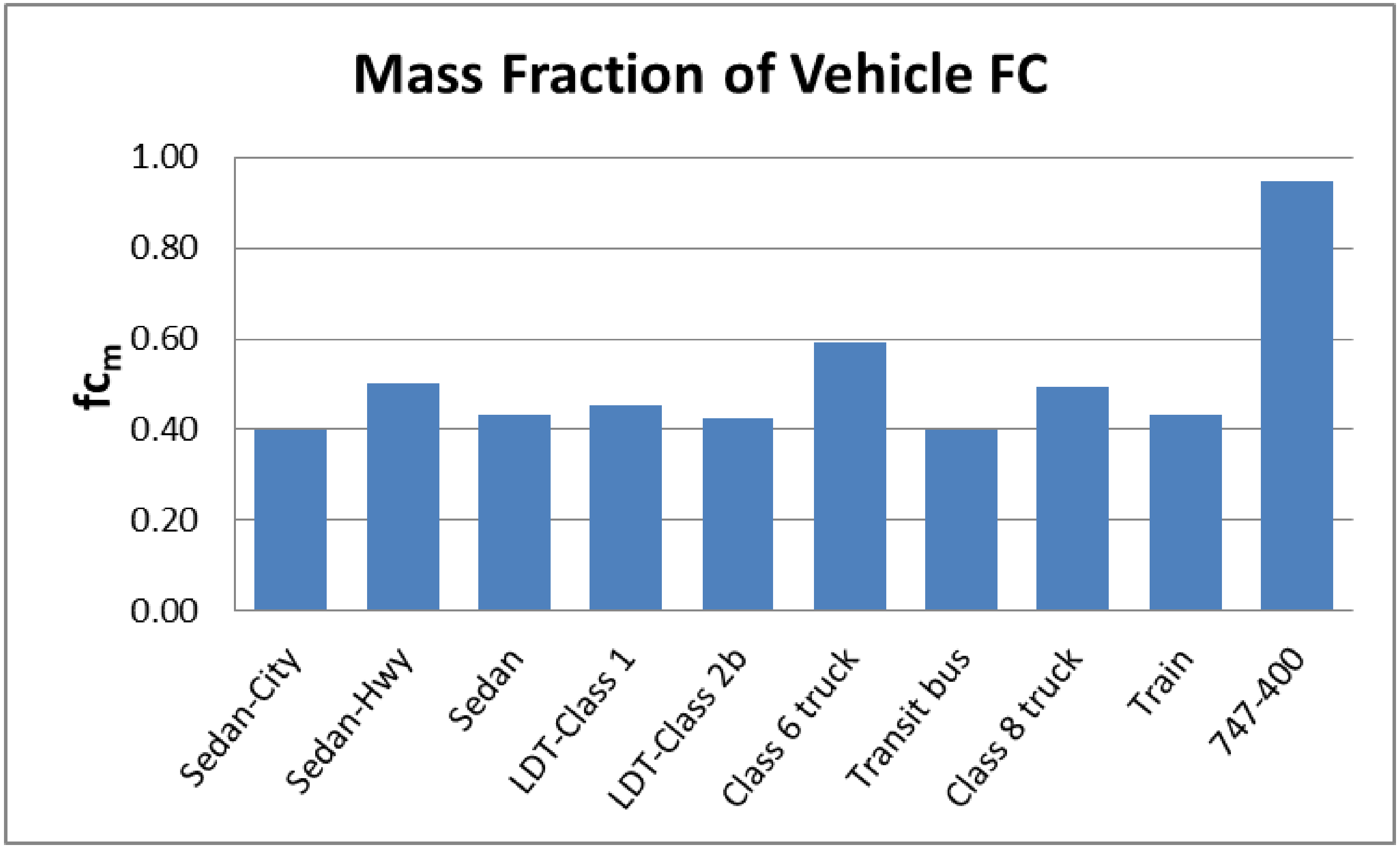


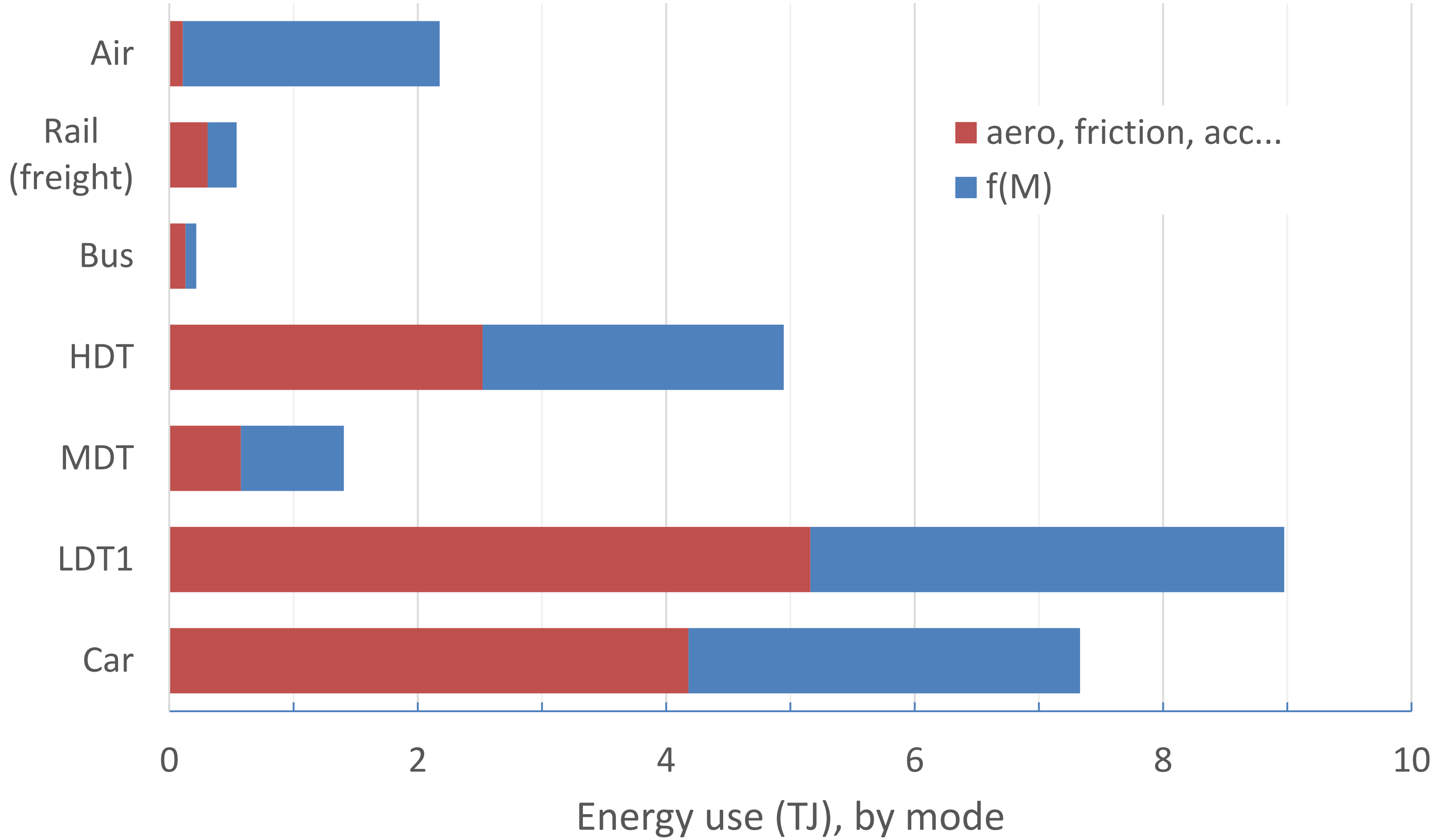
Table 2.8 in S.C. Davis, S.W. Diegel, and R.G. Bundy, 2016. Transportation Energy Data Book: Edition 35. Oak Ridge National Laboratory, Oak Ridge, TN.

FC Vehicle Mass Dependency across modes



J.L. Sullivan, G.M. Lewis, G.A. Keoleian, in review. Effect of mass on multimodal fuel consumption in moving people and freight.

Mass Component of US Fuel Consumption



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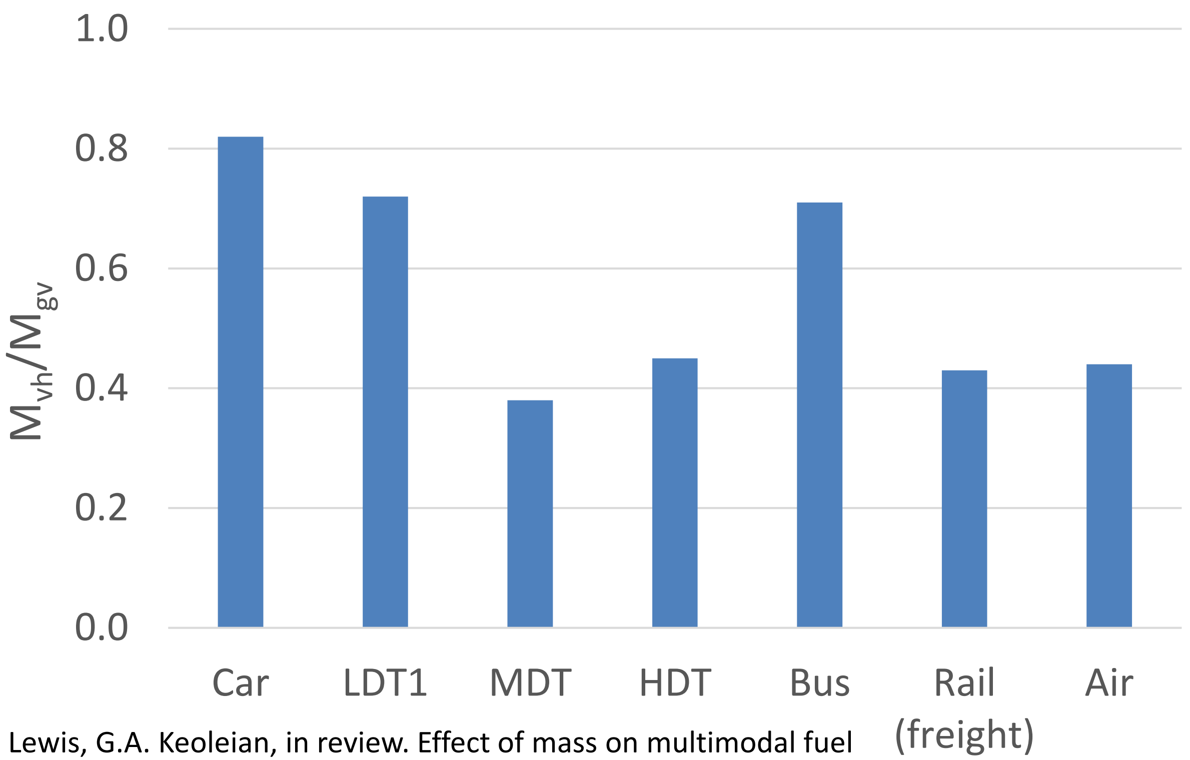
Reduction Opportunity: Vehicle Mass/Gross Vehicle Mass

- LW opportunity for OEMs is with vehicle mass
  - Ratio of M_{vh}/M_{gv}

M_{vh} = vehicle mass

M_{cargo} = cargo mass

M_{gv} = gross vehicle mass
= M_{vh} + M_{cargo}



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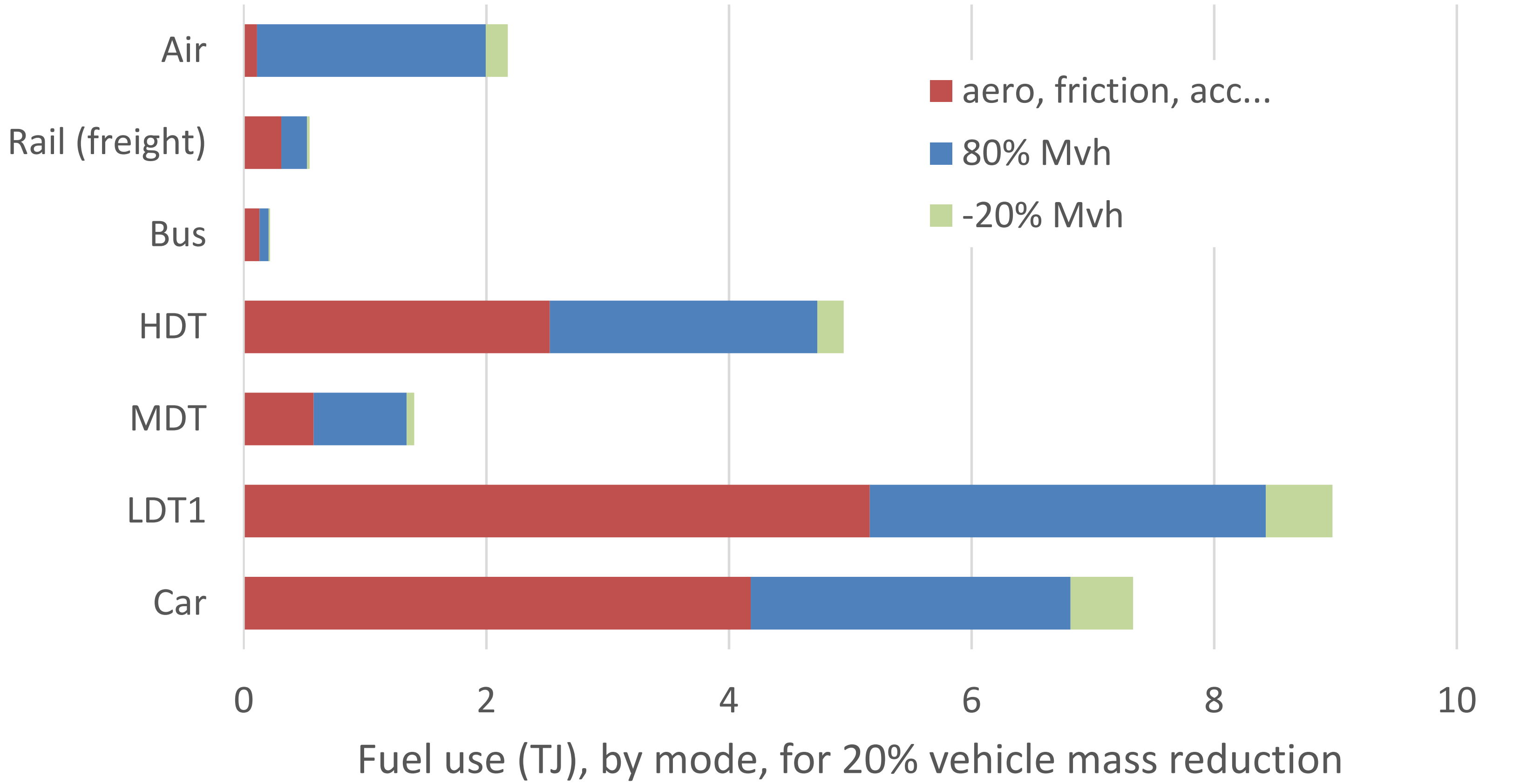
US fuel savings from 20% vehicle LW



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Basic Equations of Vehicle Motion

The general equation for **fuel consumption (FC)** of wheeled vehicles:

$$FC = F_m + F_{acc} + F_{aero} + F_f + F_l$$

where *m* denotes mass, *acc* is accessories, *aero* is aero/hydro drag, *f* is internal friction, and *l* is miscellaneous

Mass dependence of fuel consumption:

$$FC = FRV \times m + B$$

where ***FRV* is fuel reduction value**, *m* is vehicle mass, and B indicates non-mass-dependent factors

$$FRV = \frac{\Delta FC}{\Delta m}$$

FRV Modeling

- MD and HD Trucks
  - Simulation & dynamometer (HD) data
- Rail
  - Davis equation
- Aircraft
  - Breguet equation & PianoX
- Ships
  - no simple relationship between ship FC and weight (displacement).
  - our approach here is empirical, relying on data provided in a study of a set of tankers and container ships of standard design where the influence of weight on fuel consumption was estimated using a computational approach

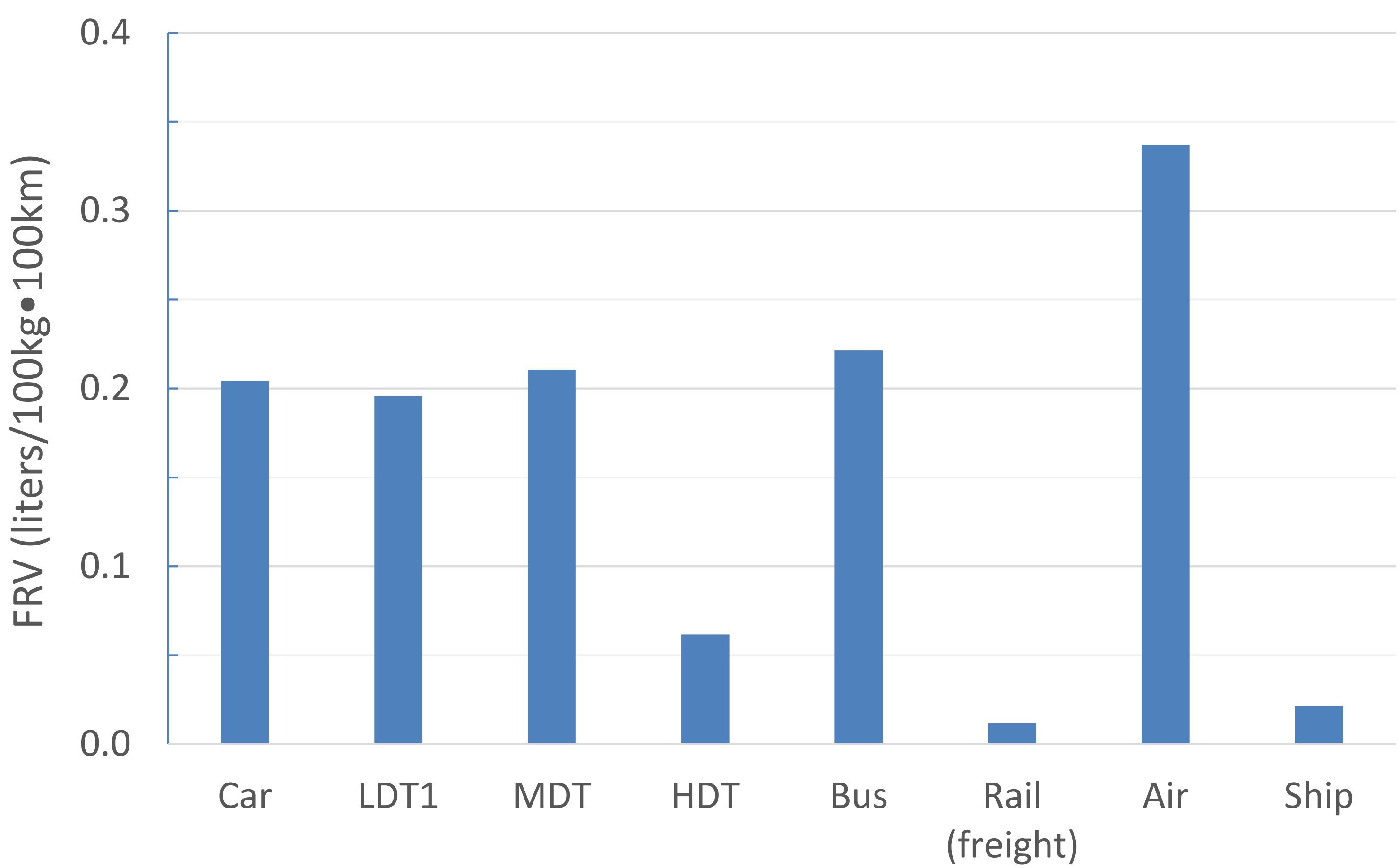
Fuel Reduction Values

Vehicle	M_{gv}[a]	M_{pyld}	M_{vh}^{b}	FC	F_{int}	FRV	Drive/Duty Cycles
	Metric Tons			iters/100 km	liters/10^4 km-kg		
Cadillac	2.04	0.14	1.90	8.7	6.38	0.20	combined cycle
Toyota Tundra	2.39	0.14	2.25	10.3	7.60	0.20	combined cycle
LDT-Class 2b[1]	4.17	1.54	2.66	18.5	1.20	0.19	combined cycle
Class 6 Truck[1]	11.79	7.35	4.47	41.8	0.57	0.21	HTUF P&D Class 6
Class 8 line haul[1]	36.28	20.59	15.69	45.1	0.22	0.062	HHDDT65
Transit Bus[1]	18.41	3.72	13.06	102	2.75	0.22	Manhattan
Freight train[c]	6,508	3,719	2,788	1,754	0.047	0.012	40 CFR 1033.530
Freight train[d]	6,508	3,719	2,788	2,704	0.073	0.027	"
Aircraft - 787-8[e]	173	23	115	583	2.54	0.30	ADC[g]
Aircraft – 747-400[f]	314	63	179	1,176	1.87	0.33	ADC[g]
Oil Tanker[2]	174,417	148,864	25,818	12,063	0.008	0.008	unknown
Container ship[2]	110,767	79,184	31,750	23,910	0.031	0.019	unknown

[a] This is the maximum operating mass as specified by the manufacturer often referred to gross vehicle mass, for planes this is takeoff weight, for cars and LDTs this is taken as engineering test weight; [b] This is the vehicle mass without passengers or payload which for vehicles on tires is curb weight (mass), for planes this is operational empty weight; [c] acceleration not included; [d] acceleration included; [e] Boeing 787-8, 242 passengers, no cargo, payload mass of passengers is 23.0 tonnes, 6,440 km flight, Ω = 35,084 kms; [f] Boeing 747-400, 350 passengers, 27.2 tonnes of cargo, 6,440 km flight, Ω = 31,012 kms; g Aircraft duty cycle; [1] (Delorme et al. 2009); 2 (American Bureau of Shipping 2013)

J.L. Sullivan, G.M. Lewis, G.A. Keoleian, in review. Effect of mass on multimodal fuel consumption in moving people and freight.

FRVs by Mode



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Fuel Intensities

Fuel Intensity (FI) can be defined as

$$FI = \frac{FC}{Cargo\ mass}$$

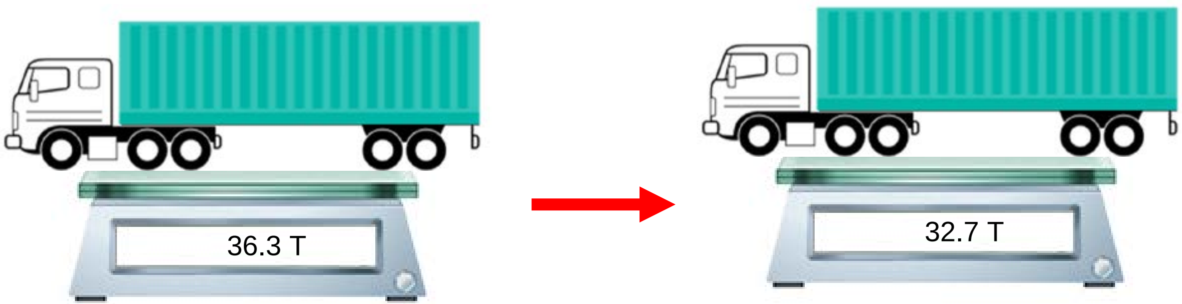
For a Class 8 line haul truck:

- Truck cargo payload: 17 tonnes
- Fuel Consumption: 45.1 liters/100 km
- $FI = 2.65\ \ liters/100\ ton \cdot km$

Fuel Intensities

If the vehicle's weight is reduced, two scenarios can occur

1. No cargo is added (volume limited)

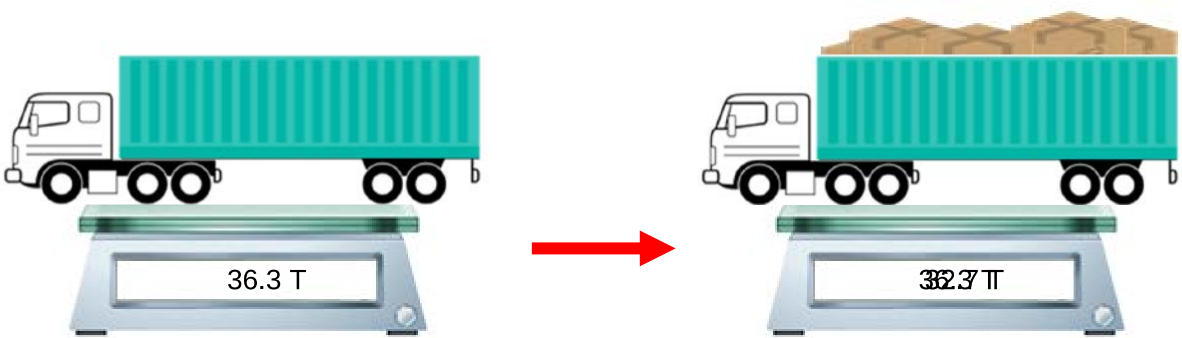


$$FI_1 = \frac{FC_{LW}}{Cargo\ mass} = \frac{42.9}{17}$$

$$FI_1 = 2.53\ liters/100T \cdot km$$

4.9% FI improvement

2. More cargo is added (mass limited)

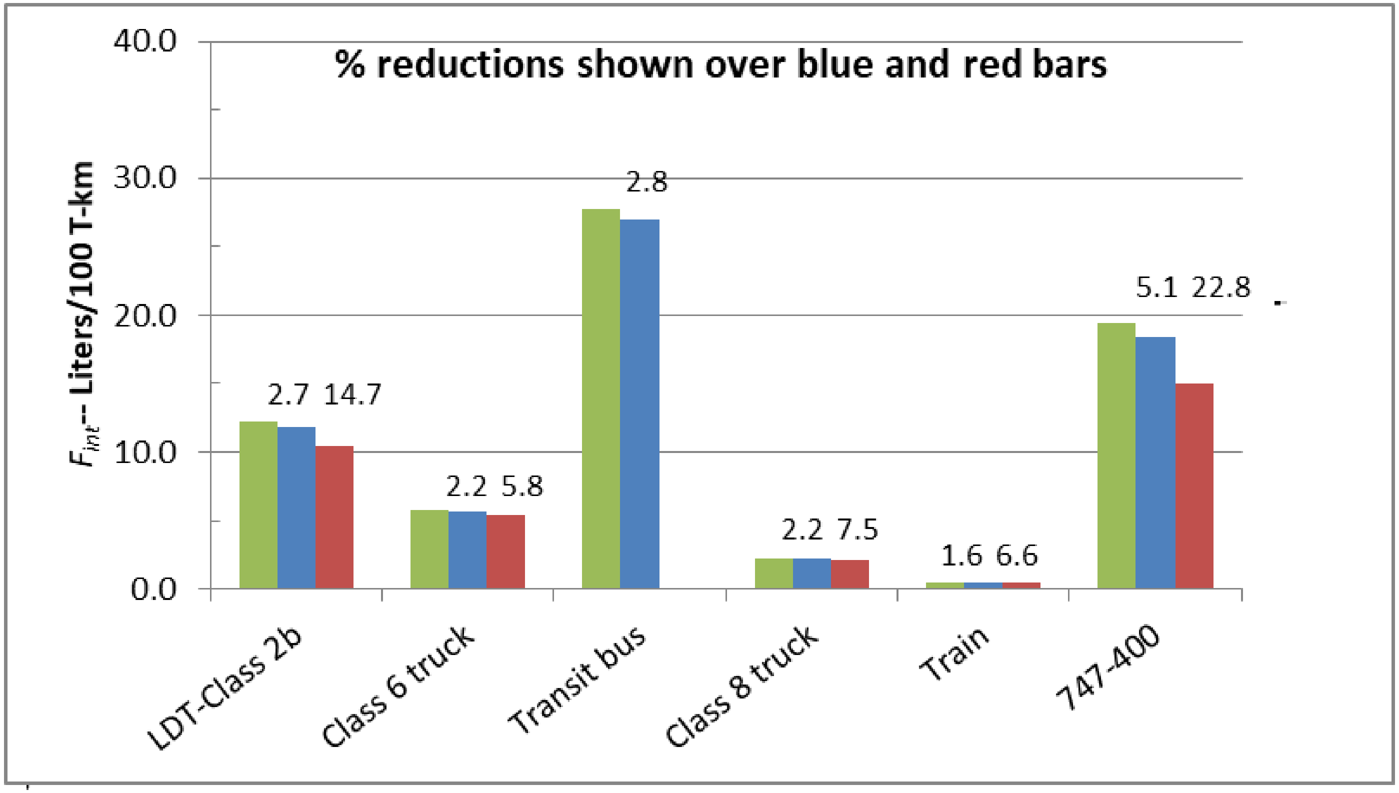


$$FI_2 = \frac{FC_{LW}}{New\ cargo\ mass} = \frac{45.1}{20.6}$$

$$FI_2 = 2.19\ liters/100T \cdot km$$

17.5% FI improvement

10% LW impact on Fuel Intensity

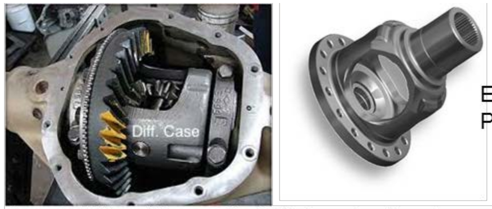


- base case values
- with their 10% vehicle mass reduced counterparts
- with their 10% vehicle mass reduced & 10% M_{cargo} increase counterparts

J.L. Sullivan, G.M. Lewis, G.A. Keoleian, in review. Effect of mass on multimodal fuel consumption in moving people and freight.

Thin-wall Cast Iron Part Example

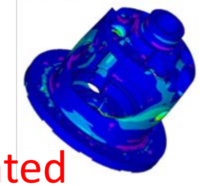
Problem	Goals and Benefits
• The ability to ***cast thin wall ductile iron (DI) castings in a high rate production environment (up to 100,000 units per year)*** is critical to leveraging the high stiffness and strength afforded by these materials.	• Goal: Develop the processes required to bring ***thin wall, vertical green sand molded DI castings to high volume production.*** • Benefit: Improved methods and alloys provide ability to ***decrease wall thicknesses by 50% and component weight by 30%-50% depending on structural loading.***



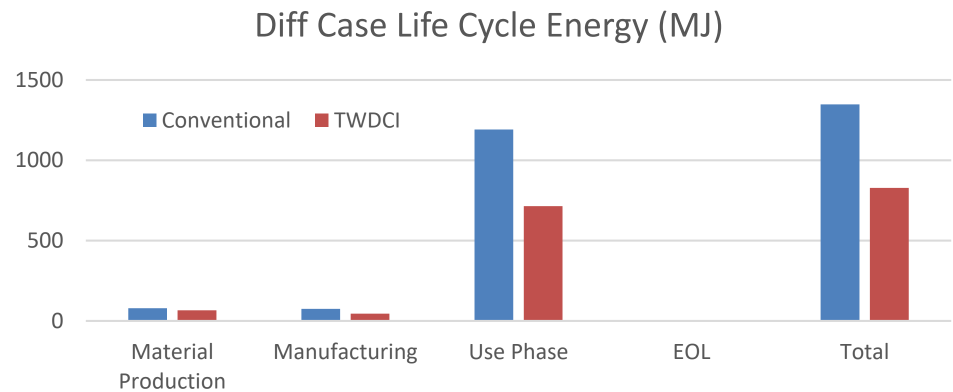
Eaton Differential Carrier
P/N: ED-39950

Figure 1 - Differential assembly (left) shows location of differential case component (right).

Images courtesy of Grede Holdings LLC



40% mass reduction demonstrated



Life cycle energy reduced by 39% for TWDCI compared to conventional cast iron differential case
(part in a mid-sized passenger internal combustion engine vehicle (ICEV) (total mass 1369 kg) with a baseline fuel economy of 26 miles per gallon (11 km/l))

Jhaveri, K., G.M. Lewis, J.L. Sullivan, and G.A. Keoleian. "Life cycle assessment of thin-wall ductile cast iron for automotive lightweighting applications." *Sustainable Materials and Technologies* (2018) 15: 1-8.

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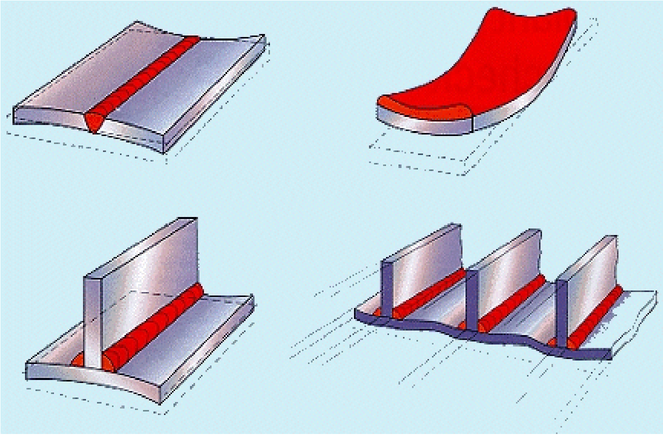
GREDE Casting Integrity · COMAU · EATON · AFS · Michigan Technological University · MIT · The Ohio State University · University of Michigan · EWI · Product Development Analysis · lift

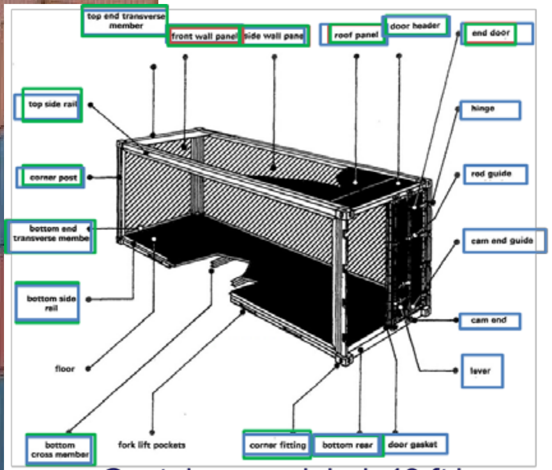
Joining & Assembly Example

Reduce warping in joining lightweight metal sheets in shipbuilding



- Flag Ship of U.S.C.G. & centerpiece of the fleet replacement program
- Most technically advanced high endurance cutter in existence

Lightweight Shipping Container Example



- Container modeled: 40 ft long, 8.5 ft high, 8 ft wide
- Conventional container mass: 3.7 tonnes

Lightweighting Scenarios:

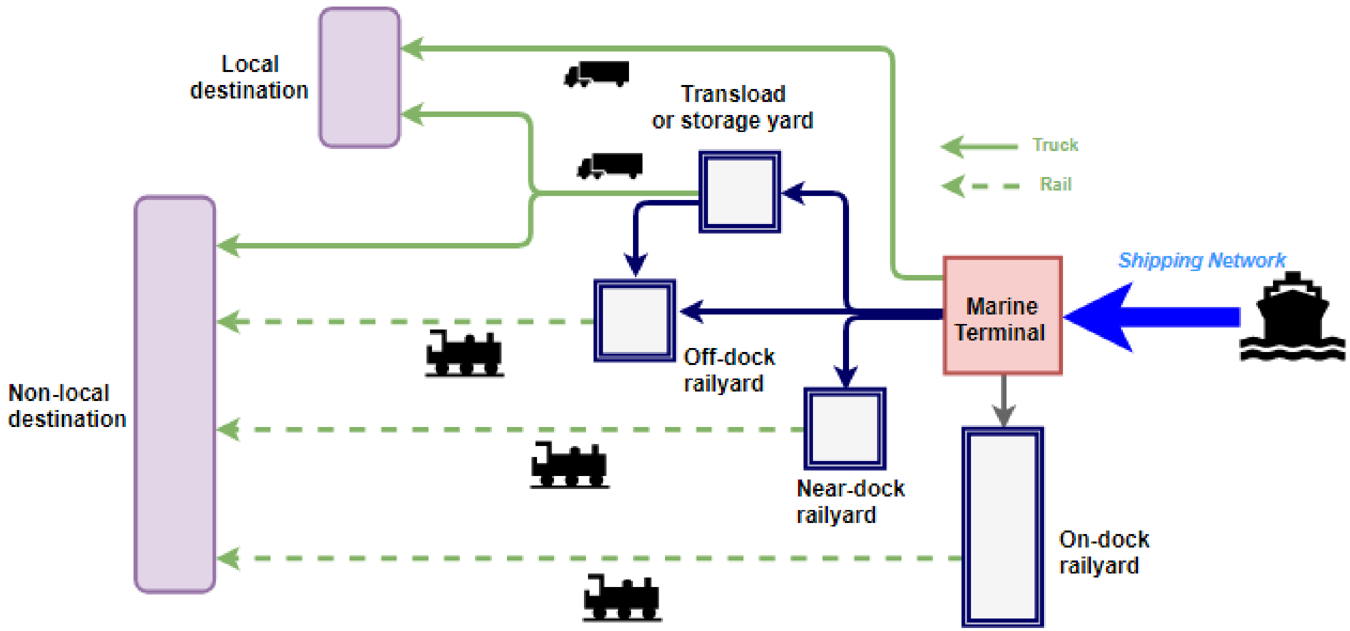
- 10% and 20% mass reduction of container **panels and roof**
  - Conventional panels and roof: 1.75 tonnes
- 10% and 20% mass reduction of **all steel** in container
  - Conventional steel: 3.09 tonnes
- Replacement of all Corten A steel with **HTS**
  - Conventional Corten A: 3.03 tonnes
  - HTS replacement: 2.58 tonnes
- Replacement of container **panels and roof** with aluminum
  - Conventional panels and roof: 1.75 tonnes
  - Al replacement: 1.12 tonnes

90% of non-bulk cargo worldwide is transported by containers, with the total world container fleet estimated at **35 million TEU (Twenty-foot Equivalent Units)**

(Castonguay, 2009; Theofanis and Boile, 2009)

C.A. Buchanan, M. Charara, J.L. Sullivan, G.M. Lewis, G.A. Keoleian, Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation, accepted for publication in *Transportation Research Part D*.

Shipping Container Logistics



Assumed container lifetime of 15 years, over which it travels ~ 5.7 million km:

Truck ~ 1 million km
Train ~ 556,000 km
Within the US

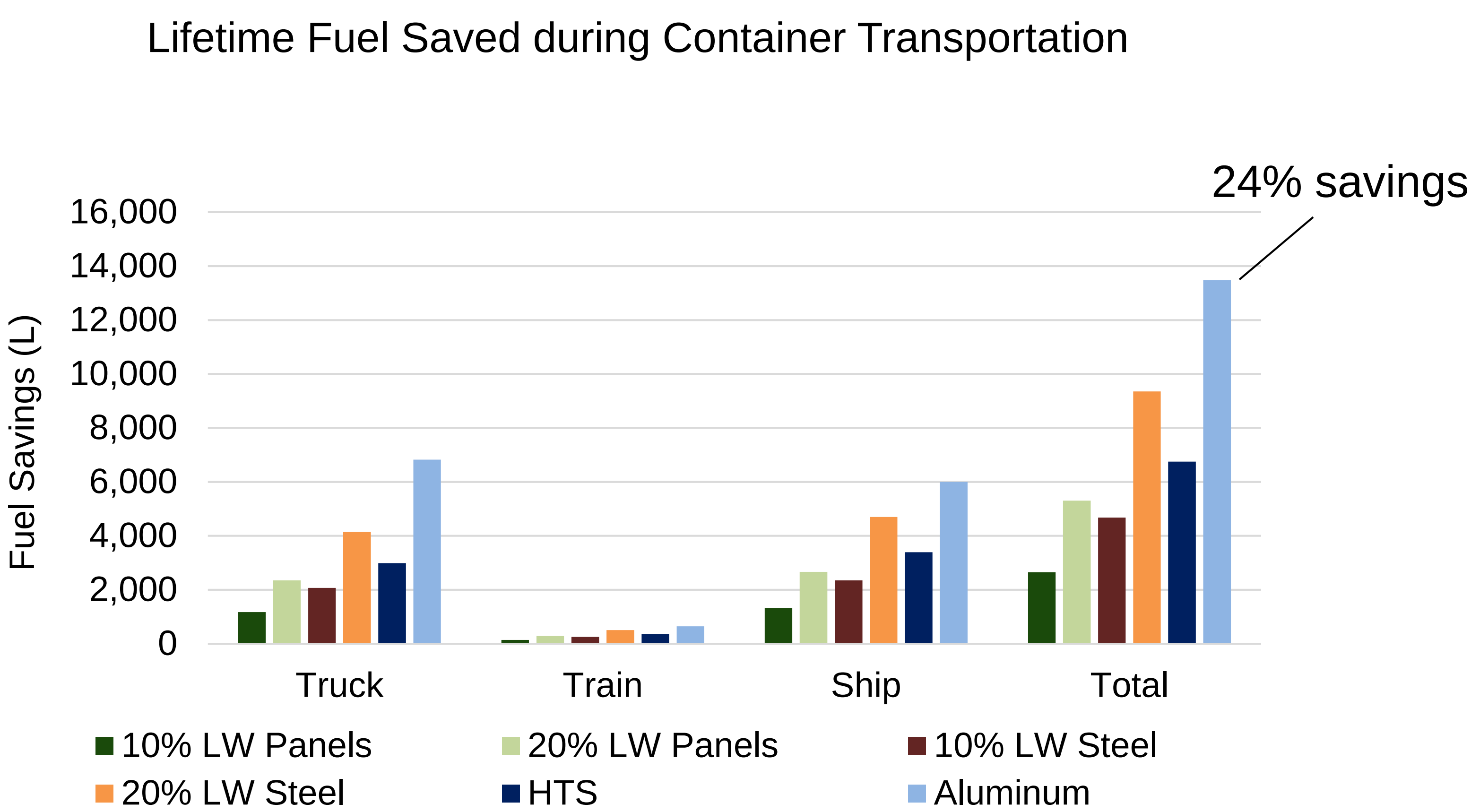
Ship ~ 4.2 million km — *To and from the US*

Truck Train Ship

Graphic source: “Cargo Movement: In Focus” – The port of Long Beach, 2008

Shipping Container Lightweighting

Fuel saved over one shipping container's lifetime (~ 5 million km).



C.A. Buchanan, M. Charara, J.L. Sullivan, G.M. Lewis, G.A. Keoleian, Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation, accepted for publication in *Transportation Research Part D*.

Shipping Container Lightweighting

- Fleet-wide results show significant savings in fuel and reduction in energy demand.
  - **U.S. fuel savings over 15 years are 5.4 – 6.9 billion liters.**

- Over 15 year U.S. multimodal container lifetime, lightweighting all steel 20% leads to a reduction in energy consumption of:
  - **0.20 – 0.26 EJ in the U.S. (truck & train)**
  - **2.7 – 3.6 EJ globally (ship)**

for reference, 2015 U.S. energy consumption was ~100 EJ

C.A. Buchanan, M. Charara, J.L. Sullivan, G.M. Lewis, G.A. Keoleian, Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation, accepted for publication in *Transportation Research Part D*.

Conclusions

- Greatest opportunities for fuel savings from LW:
  LDT1 > Cars > HDT > Air > MDT > Rail > Ship
- Cost driver greatest with Aircraft $/kg LW
- Distinguish FC vs Fuel Intensity benefits
  - Largest reductions in FI for Aircraft
- Enabling manufacturing technologies critical factor influencing material trends

Conclusions

- Evaluate full life cycle to elucidate tradeoffs from LW
- As powertrains get more efficient, LW becomes a less effective fuel saving strategy
- LW principles to guide design and implementation under development through LIFT

Team

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Additional References

- Jhaveri, K., G.M. Lewis, J.L. Sullivan, and G.A. Keoleian. “Life cycle assessment of thin-wall ductile cast iron for automotive lightweighting applications.” *Sustainable Materials and Technologies* (2018) 15: 1-8.
- Colett, J.S., J.C. Kelly, and G.A. Keoleian, “Using Nested Average Electricity Allocation Protocols to Characterize Electrical Grids in Life Cycle Assessment: A Case Study of U.S. Primary Aluminum Production” *Journal of Industrial Ecology* (2016) 20(1): 29–41.
- Kim, H.C., T.J. Wallington, J.L. Sullivan, and G.A. Keoleian, “Life Cycle Assessment of Vehicle Lightweighting: Novel Mathematical Methods to Estimate Use-Phase Fuel Consumption” *Environmental Science & Technology*, (2015) 49(16): 10209–10216.
- Johnson, J.X., C.A. McMillan, G.A. Keoleian, “Evaluation of Life Cycle Assessment Recycling Allocation Methods: The Case Study of Aluminum” *Journal of Industrial Ecology* (2013) 17(5): 700–711.
- Colett, Joseph S. (2013) “Impacts of Geographic Variation on Aluminum Lightweighted Plug-in Hybrid Electric Vehicle Greenhouse Gas Emissions.” Master's Thesis, University of Michigan: Ann Arbor 1-49.
- Keoleian, G.A. and J.L. Sullivan, “Materials challenges and opportunities for enhancing the sustainability of automobiles” *Material Research Society Bulletin*, (2012) 37(4): 365- 373.

- Kim, H-J., G. Keoleian, S.J. Skerlos, “Economic Assessment of Greenhouse Gas Emissions Reduction by Vehicle Lightweighting Using Aluminum and High-Strength Steel” *Journal of Industrial Ecology* (2011) 15(1): 64-80.
- Kim, H-J., C. McMillan, G. Keoleian, S.J. Skerlos, “Greenhouse Gas Emissions Payback for Lightweighted Vehicles using Aluminum and High Strength Steel” *Journal of Industrial Ecology* (2010) 14(6): 929-946.
- McMillan, C.A. and G.A. Keoleian “Not all Primary Aluminum is Created Equal: Life Cycle Greenhouse Gas Emissions from 1990 to 2005” *Environmental Science and Technology* (2009) 43 (5): 1571–1577.
- Keoleian, G.A., and K. Kar, “Elucidating complex design and management tradeoffs through life cycle design: air intake manifold demonstration project” *Journal of Cleaner Production* (2003) 11: 61-77.
- Keoleian, G.A. G. Lewis, R.B. Coulon, V. J. Camobreco, and H. P. Teulon “LCI Modeling Challenges and Solutions for a Complex Product System: A Mid-Sized Automobile” *Total Life Cycle Conference Proceedings, P-339*, SAE International, Warrendale, PA, (1998) Paper No. 982169: 71-84.

More Information

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